The New Finite-Range Droplet-Model Mass Table FRDM(2012) and Associated Tables of β-Decay Properties

Peter Möller, T-2

About 100 elements exist in nature. Each element is defined by its proton number, but can exist as different isotopes depending on neutron number. Only a few different, stable isotopes of each element exist, but about 100 different isotopes of many elements can exist in environments such as stars. To understand and model processes in stars and in nuclear reactors we need to know nuclear properties such as masses and decay half-lives. Because of the instability of many of these isotopes, their properties have not been experimentally measured; instead we model them. Our previous “edition” of calculated masses and decay half-lives, giving these properties for about 9,000 nuclides, is from 1992 and has been extensively used (cited about 2,000 times) in many simulation areas. By use of improved computers and enhanced physics modeling we have now developed a new and better database of nuclear masses and decay half-lives, FRDM(2012).

Our previous mass table edition, finalized in 1992 and published in 1995 [1] reproduced 1,654 experimental binding energies (masses) to an average accuracy of 0.67 MeV. Binding energies for heavy nuclei are about 1,500 MeV so this represents an accuracy to within 0.04%. The table was calculated on Cray computers. To perform the identical calculation today would take only about three hours on a modern laptop. Our current edition FRDM(2012) has taken about 50,000 CPU hours on a modern cluster. This is fairly modest by some standards, but the reasonable demand on computer time has permitted us to investigate many plausible ideas and, after thorough studies, select the optimal approaches. The steps that have taken us from FRDM(1992) to FRDM(2012) are summarized in Fig. 1. The first three steps are discussed in [2], the inclusion of the axial asymmetry shape-degree of freedom, step 4, in [3], and step 5, the effect of considering density-symmetry effects, in [4]. Step 6, improved ground-state correlations, will be discussed in a future publication. After the six successive steps were implemented, we arrived at the new mass model (table) FRDM(2012), which includes 9,318 calculated masses and reproduces 2,149 known masses in a 2003 experimental database [5] to an accuracy of better than 0.56 MeV.

Successive FRDM enhancements

Optimization (2006)
Better search for optimum FRDM parameters.
Accuracy improvement: 0.01 MeV

New mass data base (AME2003) (2006)
Better agreement than with AME1989.
Accuracy improvement: 0.04 MeV

Full 4D energy minimization (2006–2008)
Full 4D minimization($\epsilon_2, \epsilon_3, \epsilon_4, \epsilon_6$) step=0.01.
Accuracy improvement: 0.02 MeV

Axial asymmetry (2002–2006)
Also yields correct SHE gs assignments.
Accuracy improvement: 0.01 MeV

***L* variation** (2009–2011)
Accuracy improvement: 0.02 MeV

Improved gs correlation energies (2012)
Accuracy improvement: 0.01 MeV

Fig. 1. Impact of successive enhancements to FRDM(1992) with σ =0.669 MeV, leading to FRDM(2012) with σ =0.5594 MeV. The years in parentheses indicate when this particular study took place.

In Fig.2 we compare the previous and current mass tables to experimental data. To an eye unfamiliar with the subject area, the improvement may not seem substantial. However, we note that the sharp cusp in the displayed lines around N=126 are gone, the large fluctuations in the vicinity of N=82 are significantly diminished, and the (negative) bump just above N=40 is removed. Also, the lines are in general closer together and closer to zero, in particular above N=60. All these features can be expected to improve modeling of nucleosynthesis in the r-process. We have indeed found that this is the case in a first, preliminary study based on the new mass database and the associated new calculated database of β-decay properties. Initial results show that the new databases yield important improvements in the agreement between calculated r-process abundances and the observed abundances in the sun, and improve our understanding of the r-process in general [6]. It is particularly valuable that we have calculated nuclear masses and β-decay properties within a single, consistent microscopic model. This facilitates enormously the interpretation of what are the important physics processes governing the phenomena we study.

The r-process studies provide somewhat indirect evidence that we model well the properties of nuclei where the r-process occurs, which is far from stability and far from known nuclei. These nuclei have many more neutrons than nuclei that can currently be studied experimentally, in some cases 20 or so more neutrons. We can also ask what is more direct evidence that results are improved? We show in Fig. 3 the differences between the old and new calculations versus proton and neutron numbers. The plot covers about 9,000 nuclides. Most are actually unknown, but we can calculate their properties in our model. For large neutron numbers there is a growing, systematic difference. Since it is in an unknown region of nuclei, at the end of the r-process we cannot say how realistic the new results are. More testable are the “islands” of fairly large differences between the new and previous mass tables, when they occur where experimental masses are available. We have been able to verify that the new results are in better agreement with experiment. Let us focus on the region near proton number 40 and neutron number 40. In this region there are new experiments with newly measured masses

For more information contact Peter Möller at moller@lanl.gov.

Funding Acknowledgments
LANL, Laboratory Directed Research and Development Program

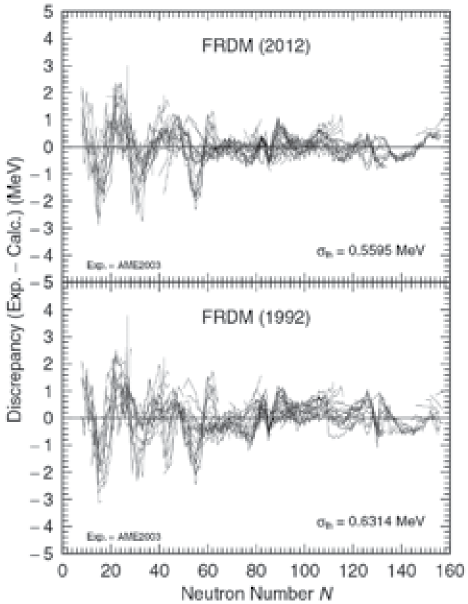

Fig. 2. Difference between experimental and calculated masses for the previous and current model. Lines connect isotopes of the same elements.

available to which the model parameters were not adjusted. In Fig.4 we compare the previous mass table (FRDM(1992)) and the current one (FRDM(2012)) to the complete set of newly measured masses [7]. Whereas the previous mass table showed large deviations in this region, with an average deviation between calculated and experimental masses of 1.10 MeV, in the new mass model the accuracy is improved to 0.34 MeV. It is outside the scope of our presentation here to discuss precisely why the new model improved the masses in this and other localized regions; suffice it to say that improved computer power permitted us to abandon some approximations made earlier and explore the model more satisfactorily; the precise reasons for the improvements are fully understood.

Based on our initial benchmarking of the new mass table we expect it will contribute to improved modeling of nucleosynthesis in stars and of many other phenomena.

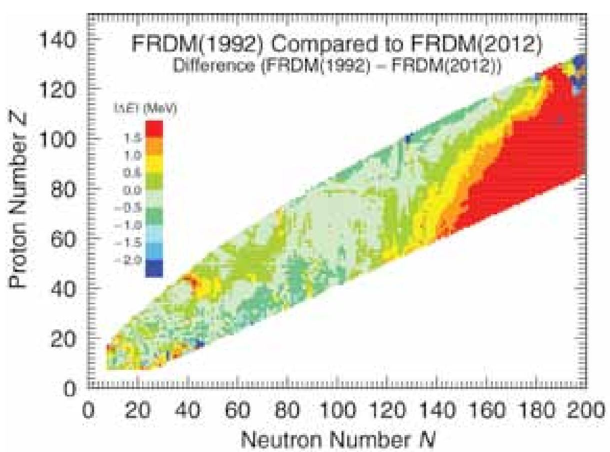

Fig. 3. Difference between the previous and current mass model masses.

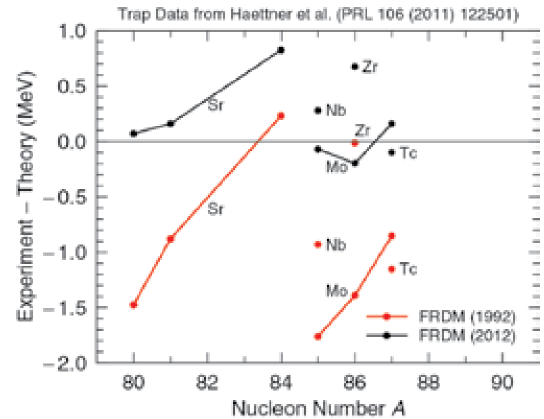

Fig 4. Difference between a complete set of masses measured in a specific recent experiment and the predictions of (1) the previous mass model FRDM(1992) and (2) the new mass model FRDM(2012). The accuracy improved from 1.10 MeV to 0.34 MeV. The newly measured masses were not used in the determination of model parameters.

[1] Moller, P. et al., *Atomic Data Nucl Data Tables* **59**, 185 (1995).

[2] Moller, P. et al., *Proc Int Conf Nuclear Data Technol*, **69**; ISBN978-2-7598-00902; http://t2.lanl.gov/molleretal/publications/nd2007.html (2008).

[3] Moller, P. et al., *Phys Rev Lett* **97**, 162502 (2006).

[4] Moller, P. et al., *Phys Rev Lett* **108,** 052501 (2012).

[5] Audi, G. et al., *Nucl Phys A* **729**, 337 (2003).

[6] Farougi, K. and Kratz, K.L. Priv. Communication.

[7] Haettner, E. et al., *Phys Rev Lett* **106**, 122501 (2011).